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SHOCK COMPRESSION OF PERICLASE AND QUARTZ AND THE  
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L.V.Al'tshuler, R.F.Trunin, and G.V.Simakov

Results are given of an investigation of the shock compressibility of periclase and quartz up to pressures of about 2.5 mbar. The shock adiabatic curves of periclase of crystalline density, the shock adiabatic curve of a rutile-like modification of quartz, and the isotherms of these substances for temperatures of 0 and 4000°K are calculated from the experimental data obtained. By comparing the compression of the earth with the  $P - \rho$  diagram, conclusions are drawn as to the chemical composition of the deep mantle.

According to the concepts developed earlier (Bibl.1 - 3), the possible components forming the deep mantle of the earth are the decomposition products of ferromagnesium silicates - magnesium oxide (periclase), quartz in its most dense rutile-like modification (stipoverite), and a certain amount of iron oxides.

To check these assumptions, the data on the shock compressibility of rocks of the olivine-pyroxene groups and of eclogite, gabbro, and a number of other rocks have been used widely in recent years in investigations (Bibl.4 - 8).

In the present article, the problem of the composition of the earth's mantle is examined on the basis of information obtained in experiments on

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\* Numbers in the margin indicate pagination in the original foreign text.

strong shock-wave compression of simpler oxide structures - periclase and quartz.

For the investigation, we used crystals of natural and artificial quartz with a density of  $\rho_0 = 2.65 \text{ gm/cm}^3$  and specimens of magnesium oxide, produced by sintering, having a density of  $\rho_0 = 3.425 \text{ gm/cm}^3$ . The pressure range encompassed by the experiments was about 2.5 mbar. Extensive experimental material on the compressibility of quartz to pressures of 700 kilobar was previously obtained by Wackerle (Bibl.9) and later by Ahrens and Gregson (Bibl.10).

The results of measuring the wave velocities  $D$  and the mass velocities of the motion of material  $u$  behind the shock-wave front, together with the pressures of shock compression  $P = \rho_0 Du$ , and the densities  $\rho = \rho_0 D(D - u)^{-1}$  are given in Table 1.

TABLE 1

Investigated Substance	Parameters of Shock Waves				Investigated Substance	Parameters of Shock Waves			
	$D$ , km/sec	$U$ , km/sec	$P \cdot 10^{-4}$ , bar	$\rho$ , g/cm <sup>3</sup>		$D$ , km/sec	$U$ , km/sec	$P \cdot 10^{-4}$ , bar	$\rho$ , g/cm <sup>3</sup>
Periclase, $\rho_0 = 3.425 \text{ g/cm}^3$	7.63	1.32	34.50	4.140	Quartz $\rho_0 = 2.65 \text{ g/cm}^3$	7.18	3.13	59.5	4.70
	9.31	2.52	80.30	4.605		8.54	3.92	88.7	4.385
	13.42	5.62	258.10	5.89		12.01	6.2	188.4	5.48

The experimental points obtained reveal the position of the shock-compression curves (Hugoniot's adiabatic curves)  $P_H$  (Fig.1). These points also yield, with sufficient reliability, the adiabatic curves of periclase and stipo-verite corresponding to the initial states of the crystallographic density of the specimen ( $\rho_{0cr} = 3.62 \text{ gm/cm}^3$  for periclase and  $4.35 \text{ gm/cm}^3$  for stipoverite) and the isotherms characterizing the behavior of the investigated minerals at pressures and temperatures of the deep mantle of the earth.

The slope of the shock-compression adiabatic curves  $P_H(\rho, \rho_0, E_0)$  depend

(Bibl.11) on the thermodynamic characteristics of the medium at shock-compression pressures as well as on the energies  $E_0$  and the densities  $\rho_0$  of the initial states. If the initial states differ only in density, the pressure on the adiabatic curve of a dense substance (with  $\rho_0 = \rho_{0cr}$ ) will be

$$P_H(\rho, \rho_{0cr}) = P_H(\rho, \rho_0) \frac{h - \rho_0^{-1}\rho}{h - \rho_{0cr}^{-1}\rho};$$

$$h = 1 + \frac{2}{\gamma}. \quad (1)$$

The parameter  $\gamma$  entering into eq.(1), for a compressible medium, determines the ratio of the thermal pressure to the density of thermal energy. Its initial

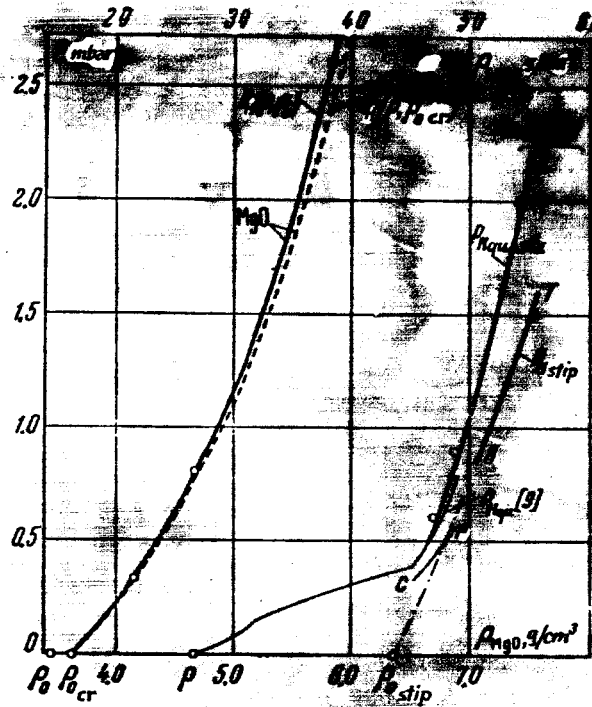


Fig.1 Shock-Compression Adiabatic Curves of Periclase, Quartz, and Stipoverite

value, at  $\rho = \rho_0$  for periclase, is about 1.35. Taking into account the general tendency toward a decrease of  $\gamma$  with the degree of compression (Bibl.7), we will assume here, with an accuracy sufficient for our purposes, that  $\gamma_{MgO} = \text{const} = 1.0$  and, correspondingly, that  $h = 3$ . The adiabatic curve of dense

periclase calculated from eq.(1) is shown in Fig.1 by a dashed curve  $P_H(\rho, \rho_{ocr})$ .

Knowing the adiabatic curve  $P_H(\rho, \rho_{ocr})$  and the parameter  $h$ , the pressure of cold compression on the zero isotherm is determined as defined elsewhere (Bibl.12)

$$P_x(\rho) = 2(h-1)^{-1} \rho^{h-1} \int_{\rho_{ocr}}^{\rho} P_H(h - \rho \rho_{ocr}^{-1}) \rho^{-h-1} d\rho + (h-1)^{-1} (h - \rho \rho_{ocr}^{-1}) \quad (2)$$

and the slope of the isotherms for  $T > 0$

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$$P_T(\rho, T) = P_x(\rho) + \gamma \rho c_v T. \quad (3)$$

The parameters of the shock-compression adiabatic curve of periclase [calculated from eq.(1)] and its isotherms for temperatures of 0 and 4000°K are given on the left-hand side of Table 2.

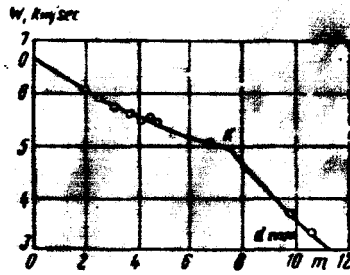


Fig.2 Velocity of Free Surface vs. Thickness of Specimen d

The curve segment OK represents the relaxation of pressures at the wave front as a result of phase change; km is attenuation of the shock wave under the effect of relieving waves

To find the shock-compression adiabatic curves of stipoverite, McQueen, Fritz, and Marsh (Bibl.13) used the data of Wackerle (Bibl.9) on the compression of quartz (Fig.1). The position of the sought curve was calculated by the easily derivable relation

$$P_{Hst} = P_{Hqu} \frac{h - \rho \rho_{qu}^{-1}}{h - \rho \rho_{st}^{-1}} + \frac{2\rho(E_{ost} - E_{aqu})}{h - \rho \rho_{st}^{-1}}, \quad (4)$$

taking into account the difference of the initial states of the two phases both with respect to densities and to energies.

According to McQueen (Bibl.13),  $\gamma = 0.9$ ,  $h = 3.22$ , and  $E_{0st} - E_{0q} = 1.5 \times 10^{10}$  erg/gm. The function  $P_{Hq}$  entering into the right-hand side of eq.(4) is the experimental adiabatic curve of quartz above the pressures of its phase changes (for  $P \geq 400$  kilobar). This curve rather characterizes the nonequilibrium mixture of stipovertite and the initial structure of the  $\alpha$ -quartz. This assumption is substantiated by the slope of the adiabatic curve obtained by McQueen (Bibl.13) from eq.(4). Upon extrapolation down to zero pressure, the curve by-passes the initial state of the dense phase ( $P = 0$ ;  $\rho_0 = 4.35$  gm/cm) deviating from it to the left, toward the region of lower densities (curve CP in Fig.1). Its corrected position which, according to McQueen (Bibl.13), represents the behavior of pure stipovertite, is shown in Fig.1 by a dot-dash line. The incompleteness of phase changes at pressures of about 500 kilobar is also indicated by the relaxation of pressures accompanying the travel of shock waves through the specimen (Fig.2). The experiments revealing this phenomenon were performed by the author after a method described elsewhere (Bibl.7, 19).

The states recorded at many high pressures of 1 - 2.5 mbar characterize the molten state of the material heated to temperatures of 15 - 25,000°. At these temperatures, the ions of oxygen and silicon and thermally excited electrons acquire the thermodynamic properties of highly dense plasma with an effective Grüneisen ratio  $\bar{\gamma}$  close to 0.6. [For excited electrons,  $\gamma_e \approx 0.5$  (Bibl.14, 15), for ions in an effectively gaseous state,  $\gamma^+ \approx 0.7$ , and, thus  $\bar{\gamma} \approx 0.6$ ,  $h = 4.32$ .]

The upper branch of the adiabatic curve of stipovertite, calculated from the high-temperature value of  $h$ , is shown in Fig.1 by the curve AT. Its slope is approximated with reasonable accuracy by the equation of the adiabatic curve proposed by McQueen (Bibl.13).

The parameters of the adiabatic curve corresponding to the  $D - u$  relation,  $D = 10.27 + 0.880 u^*$  are shown on the right-hand side of Table 2, together with the coordinates of the isotherms calculated by eq.(3). (In these calculations 4 pertaining to temperatures not exceeding several thousands of degrees, we used the low-temperature values of  $\gamma = 0.9$  and  $h = 3.22$ .)

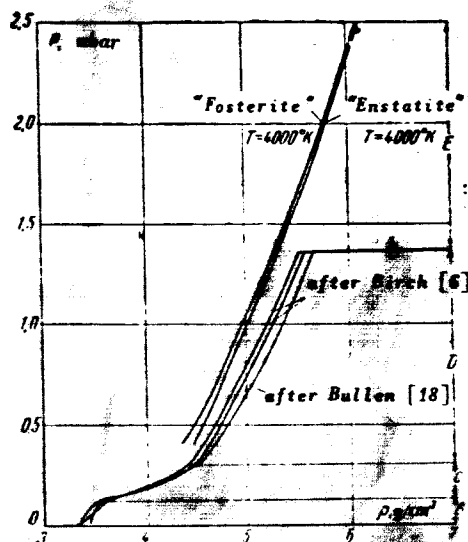


Fig.3 Isothermal Compression of Mixtures of Periclase and Stipoverite and the  $P - \rho$  Diagrams of the Earth's Mantle after Bullen and Birch  
 "Forsterite" - isotherm corresponding to stoichiometric proportion of oxides in forsterite; "Enstatite" - isotherm corresponding to stoichiometric proportion of oxides in enstatite

Having at our disposal the isotherms of  $MgO$  and  $SiO_2$ , we can now construct the isotherms of compression of their mixtures corresponding to stoichiometric proportions of magnesium and silicon oxides in enstatite and forsterite (60%  $SiO_2$  and 40%  $MgO$ , and 43%  $SiO_2$  and 57%  $MgO$  respectively).

The isotherms are calculated by the addition rule of specific volumes ( $\rho^{-1}$ ) of components at thermodynamic equilibrium:  $\alpha \rho_{SiO_2}^{-1} + (1 - \alpha) \rho_{MgO}^{-1} = \rho_{mix}^{-1}$

\* According to (Bibl.13) a very close expression  $D = 10 + 1.0 u$  is the equation of the adiabatic curve in  $D - u$  coordinates.

( $\alpha$  is the percent by weight of  $\text{SiO}_2$ ;  $\rho_{\text{mix}}^{-1}$  is the specific volume of the mixture).

For a temperature of  $4000^\circ\text{K}$  characterizing (Bibl.16, 17) the thermal conditions of the deep mantle, the isotherms of the two components are compared in Fig.3 with the compression diagrams of the earth according to Bullen (Bibl.18) (model A) and Birch (Bibl.6).

Just as the adiabatic curves of rocks (Bibl.7, 8) with a predominating content of forsterite and enstatite, the isotherms obtained in this work for  $P > 700$  kilobar almost coincide.

Running approximately parallel to the compression curve for the D region, they deviate from Bullen's model A for 1.2 mbar by  $0.37 \text{ gm/cm}^3$  and from Birch's curves by  $0.22 - 0.28 \text{ gm/cm}^3$ . A right shift of the isotherms until they coincide with the geophysical curves requires the "introduction" of rather appreciable quantities of iron oxides into the composition of the mantle. Thus, for the isotherms to coincide with Bullen's model, the D region should consist of about 18% iron oxides and about 82% of a mixture of stiperite and periclase; for Birch's model, about 12% iron oxides and about 88% stiperite and periclase. According to another author (Bibl.8), the B region has a close content of iron oxides (about 10%). Thus, for Birch's  $P - \rho$  diagrams, the chemical composition of all regions of the mantle can be taken as identical, and the anomalous increase in density of the C region as a whole can be attributed to phase changes of the ferromagnesium silicates, to their decomposition to a mixture of densely packed oxides of silicon, magnesium, and iron.

The attractive hypotheses of a homogeneous composition of the mantle are not unequivocal, mainly by virtue of the ambiguity of the geophysical characteristics of the D region. At present there exists no completely reliable phase



diagram of the oxides in question, at the pressures and temperatures of interest here.

We can assume with sufficient justification, however, that at the high pressures of the inner mantle, the combination of the densest structures studied in the present work is thermodynamically stable.

TABLE 2

P · 10 <sup>-4</sup> bar	Density g/cm <sup>3</sup>					
	MgO			SiO <sub>2</sub>		
	$\rho_R$	$\rho_T = 0^\circ \text{K}$	$\rho_T = 4000^\circ \text{K}$	$\rho_R$	$\rho_T = 0^\circ \text{K}$	$\rho_T = 4000^\circ \text{K}$
0	3.62	3.62	3.455	4.35	4.35	4.28
20	3.95	3.968	3.806	4.535	4.535	4.48
40	4.245	4.257	4.11	4.708	4.710	4.65
60	4.492	4.517	4.37	4.87	4.872	4.81
80	4.721	4.762	4.615	5.03	5.033	4.975
100	4.93	4.976	4.84	5.18	5.19	5.13
120	5.168	5.17	5.05	5.33	5.34	5.278
140	5.27	5.34	5.23	5.47	5.483	5.42
160	5.41	5.508	5.40	5.61	5.63	5.565
180	5.535	5.658	5.555	5.74	5.77	5.705
200	5.658	5.805	5.71	5.87	5.91	5.846
220	5.765	5.95	5.853	6.00	6.053	5.987
240	5.881	6.092	5.994	6.12	6.18	6.123
260	5.998	6.23	6.13	6.235	6.33	6.268

The above estimates of the iron content in the D region differ from the data given elsewhere (Bibl.8) and, at that, toward the lesser side. The results obtained by Trunin (Bibl.8) are based on a study of rocks consisting mainly of forsterite and enstatite. Despite the presence in the specimens of a weighty 15 iron addition, equivalent to about a 10% content of iron oxides, the compression curves (Bibl.8) and the geotherms plotted from them pass along the P -  $\rho$  diagram in approximately the same manner as the curves plotted in this work from the adiabatic curves of pure minerals.

This contradiction is explained by the inertia of the phase changes, associated with complex rearrangements of the crystal lattice.

We can assume that, under the conditions of shock-wave compression, the

phase changes in forsterite and enstatite do not lead to the formation of equilibrium phase compositions from the densest structures. From this point of view, the conclusions of the present study, based on an investigation of simple compounds representing the end products of silicate decomposition, are more reliable.

#### BIBLIOGRAPHY

1. Ringwood, A.E.: Mineralogical Constitution of the Deep Mantle. J. Geophys. Res., Vol.67, No.10, 1962.
2. Stishov, S.M.: On the Internal Structure of the Earth (O vnutrennem stroenii Zemli). Geokhimiya, No.8, 1962.
3. Green, D.H. and Ringwood, A.E.: Minerals Assemblages in a Model Mantle Composition. J. Geophys. Res., Vol.68, No.3, 1963.
4. Hughes, D.S. and McQueen, R.G.: Density of Basic Rocks at Very High Pressures. Trans. Am. Geophys. Union, Vol.39, No.5, 1958.
5. Al'tshuler, L.V. and Kormer, S.B.: On the Internal Structure of the Earth (O vnutrennem stroenii Zemli). Izv. Akad. Nauk SSSR, Ser. Geofiz., No.1, 1961.
6. Birch, F.: Density and Composition of Mantle and Core. J. Geophys. Res., Vol.69, No.20, 1964.
7. Al'tshuler, L.V.: Use of Shock Waves in High-Pressure Physics (Primeneniye udarnykh voln v fizike vysokikh davleniy). Usp. Fiz. Nauk, Vol.85, No.2, 1965.
8. Trunin, R.F., Gon'shakov, V.I., Simakov, G.V., and Galdin, N.Ye.: Investigation of the Shock Compressibility of Eleven Rocks Exposed to High Pressures and Temperatures of Shock Compression (Issledovaniye udarnoy szhimayemosti

- odinnadtsati gornykh porod pod deystviyem vysokikh davleniy i temperatur udarnogo szhatiya). Izv. Akad. Nauk SSSR, Fizika Zemli, No.9, 1965.
9. Wackerle, I.: Shock-Wave Compression of Quartz. J. Appl. Phys., Vol.33, 1962.
  10. Ahrens, T.I. and Gregson, V.G.: Shock-Compression of Crystal Rocks Data for Quartz, Calcite, and Plagioclase Rocks. J. Geophys. Res., Vol.69, No.22, 1964.
  11. Zel'dovich, Ya.B. and Rayzer, Yu.P.: Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena (Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavleniy). Moscow, 1963.
  12. Al'tshuler, L.V., Krupnikov, K.K., Ledenev, B.N., Zhuchikhin, V.N., and 6 Brazhnik, M.I.: Dynamic Compressibility and the Equation of State for Iron at High Pressures (Dinamicheskaya szhimayemost' i uravneniye sostoyaniya zheleza pri vysokikh davleniyakh). Zh. Eksperim. i Teor. Fiz., Vol.34, 1958.
  13. McQueen, R.G., Fritz, J.N., and Marsh, S.P.: On the Equation of State of Stipoverite. J. Geophys. Res., Vol.68, No.8, 1963.
  14. Gilvarry, J.J.: Grüneisen Law and the Fusion Curve at High Pressure. Phys. Rev., Vol.102, No.2, 1956.
  15. Kormer, S.B., Urtin, V.D., and Popova, L.T.: Interpolation Equation of State and its Application to Describing Experimental Data on Shock Compression of Metals (Interpolyatsionnoye uravneniye sostoyaniya i yego prilozheniye k opisaniyu eksperimental'nykh dannykh po udarnomu szhatiyu metallov). Fiz. Tverd. Tela, Vol.3, No.7, 1961.
  16. Lyubimova, Ye.A.: Thermoelastic Stresses inside the Earth (Termouprugiye napryazheniya vnutri zemnogo shara). Tr. Inst. Fiz. Zemli, No.20 (187),

1962.

17. Lyubimova, N.A.: Thermal History of the Earth with Consideration of Variable Thermal Conductivity of its Mantle. J. Roy. Astron. Soc., Vol.I, No.2, 1958.
18. Bullen, K.Ye.: Physics and Chemistry of the Earth (Fizika i khimiya Zemli). Izd. Inostr. Lit., Moscow, 1958.
19. Al'tshuler, L.V., Kormer, S.B., Brazhnik, M.I., Vladimirov, L.A., Speranskaya, M.P., and Funtikov, A.I.: Isentropic Compressibility of Aluminum, Copper, Lead, and Iron at High Pressures (Izentropicheskaya szhimayemost' alyuminiya, medi, svintsa i zheleza pri vysokikh davleniyakh). Zh. Eksperim. i Teor. Fiz., Vol.34, No.4, 1960.